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(54) GAS GENERATING SYSTEM

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Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] This invention relates to electrically operated propellants, and more particularly to controlling the ignition conditions of the propellant to efficiently and controllably ignite, burn and consume the electrically operated propellants in a manner that is scalable to combust an increased propellant mass for larger gas generation systems.

Description of the Related Art

[0002] All propellants are a combination of oxidizer, fuel, binder and additives. The oxidizer provides oxygen required to burn the fuel. The binder provides a structural material to bind the fuel and oxidizer. The binder itself is a fuel. Additional fuel may or may not be required. Additives may be used for a variety of purposes including to assist curing of the propellant, to control the burn rate, etc. Propellant may be used for gas generators, rocket motors, air bags and the like. It is desirable that substantially all of the propellant is or can be consumed.

[0003] Solid rocket motor (SRM) propellants are ignited thermally and burn vigorously to completion of the propellant. SRM propellants typically exhibit a designed burn rate and consume substantially all of the propellant. However, the burn rate cannot be independently controlled. Furthermore, once ignited, SRM propellants cannot be "turned off' except by a violent and uncontrolled depressurization. The most common oxidizer for SRM propellants is a solid ammonium perchlorate (AP). The resulting SRM propellant ignites in response to heat but is electrically inert.

[0004] Electrically operated propellants are ignited by application of an electric input. In a simple configuration, a voltage is applied between parallel wires embedded in the propellant. Application of the voltage across the propellant creates a current density (J) = current (I)/area (A) of the propellant. The current density J must exceed an ignition threshold of the propellant to ignite and bum. To support electrical operation, the oxidizer is "ionic" in the sense of providing free-flowing ions necessary for electrical control. The burn rate of the propellant may be controlled via the electric input.

[0005] Certain formulations of the propellant, and more specifically the oxidizer, allow combustion to be extinguished by interruption of the electric input as long as the chamber pressure remains less than a self-sustaining threshold pressure. The propellant may be reignited by reapplication of the electric input. Sawka's hydroxyl-ammonium nitrate (HAN) based propellant (US 8,857,338) exhibits a threshold of about 150 psi. Villarreal's perchlorate-based propellant (US 8,950,329) can be configured to exhibit a threshold greater than 200, 500, 1.500 and 2,000 psi. 1 psi = 6894.76 N/m^2. These higher threshold pressures allow for more practical applications in which the combustion may be turned on and off at elevated chamber pressures. For these reasons, electrically operated propellants are an attractive option to more mature SRM propellants. A challenge to achieve wide spread use is to provide an electrode configuration that provides for control of the burn rate and efficient consumption of substantially all of the propellant, and one that is scalable to combust greater propellant mass to support larger gas generation systems.

[0006] U.S. Patent No. 8,857,338 "Electrode Ignition and Control of Electrically Ignitable Materials" also discloses an apparatus for providing electrically initiated and/or controlled combustion of electrically ignitable propellants is provided. In one example, the apparatus includes a volume of electrically ignitable propellant (solid and/or liquid), which is capable of self-sustaining combustion, and two (or more) electrodes operable to ignite the propellant. The apparatus may further include a power supply and controller in electrical communication with the electrodes for supplying a potential across the electrodes to initiate combustion of the propellant and/or control the rate of combustion of the propellant. For instance, by increasing or decreasing the power and current supplied through the propellant the rate of combustion may be varied.

[0007] Various configurations and geometries of the propellant, electrodes, and apparatus are described. In one example, the electrodes are in electrical contact with the electrically ignitable propellant and are supplied a direct current, which may cause combustion of the electrically ignitable propellant at the contact location of the positive electrode with the electrically ignitable propellant. In another example, the electrodes are supplied an alternating current, which may initiate nearly simultaneously combustion of the electrically ignitable propellant at the contact locations of the electrodes with the electrically ignitable propellant. In some examples, one or more of the electrodes may include an insulator material insulating a portion of the electrode from the electrically ignitable propellant (which may burn away with combustion of the propellant).

[0008] In one configuration, a center insulated wire electrode is positioned along the axis of a cylindrical electrode in a coaxial configuration around the propellant (FIGs. 1a-1b). As combustion of the propellant is initiated, the insulation burns away and the propellant regresses along the axis. In another configuration, parallel plate electrodes are positioned to either side of the propellant (FIGs 3a-3b). In the FIG. 3a embodiment, one of the parallel plate electrodes is insulated to produce combustion of the propellant to spread across the gain-end to the outer cathode. The combustion of the propellant propagates to the left along the axis of the structure, in a generally uniform manner as illustrated. In contrast, in the FIG. 3b embodiment both of the plate electrodes are uninsulated. The propellant is broadly ignited along much of or the entire length of the positive electrode.

[0009] US 2008/087003 discloses an apparatus and method to control ignition, combustion burn rate, extinguishment, and reignition of solid propellant. The thrusters disclosed are directed to electrically controllable rocket motors based on a class of controllable propellants called electrically controlled extinguishable solid propellants.

[0010] US 8,464,640 discloses a thruster stack assembly including a plurality of grain elements having a common core region, where each grain element comprises a volume of electrically ignitable propellant. The thruster stack assembly further includes electrodes associated with the plurality of grain elements that are adapted for selectively igniting the grain elements.

SUMMARY OF THE INVENTION

[0011] The following is a summary of the invention in order to provide a basic understanding of some aspects of the invention. This summary is not intended to identify key or critical elements of the invention or to delineate the scope of the invention. Its sole purpose is to present some concepts of the invention in a simplified form as a prelude to the more detailed description and the defining claims that are presented later.

[0012] The present invention is a gas generation system according to claim 1. It provides electrode ignition and control of electrically operated propellants that efficiently consumes the available propellant and is scalable to combust increased propellant mass for larger gas generation systems.

[0013] This is accomplished with different configurations of electrode structures and electrically operated propellant in a gas generation system that provides an ignition condition at an ignition surface between four or more electrodes that satisfies three criteria. First, the current density J along an axis normal to the ignition surface exhibits a decreasing gradient. Second, the current density J across the ignition surface is approximately constant. Third, the current density J at the ignition surface exceeds an ignition threshold. Configurations that satisfy all criteria and particularly the second criterion are critical to scalability. Otherwise, the propellant will only ignite at or near the point of maximum current density J, typically at the surface of one of the electrodes, which hinders the ability to control the burn rate and leaves a lot of propellant unconsumed. To satisfy the second criterion, the contour of the ignition surface is designed and built to match the contour of current lines between the electrodes. At least 95% of the available mass of the propellant is consumed. If combustion is interrupted, that means at least 95% of the available mass up to the point of extinguishment.

[0014] Different embodiments of a gas generation system may be configured to consume at least 10 grams, 100 grams, 1,000 grams or more of electrically operated propellant.

[0015] In an embodiment, the electrically operated propellant comprises an ionic perchlorate-based oxidizer such that the propellant has a self-sustaining threshold pressure of at least 500 psi at which the propellant once ignited by the electrical input cannot be extinguished and below which the propellant can be extinguished by interruption of the electrical input. Combustion may be turned off and on per application requirements. The self-sustaining threshold may be 1,000, 1,500, 2,000 psi or higher.

[0016] In an embodiment, a conducting or non-conducting additive is added to the electrically operated propellant. The concentration of the additive follows a gradient along the axis normal to the ignition surface. A conductive additive may be a metal powder and a non-conducting additive may be an electrical insulating plastic. This produces the decreasing gradient in current density J along the axis. The electrodes may be configured as parallel plate or angled electrodes.

[0017] In an example, not claimed, each of the electrodes comprises a plurality of sub-electrodes. A network of relays and switches selectively activate one pair of sub-electrodes at a time to propagate the electrical signal along the axis. The current density J constitutes a maximum pulse at the activated pair of sub-electrodes followed by a null current density at the following un-activated pairs of sub-electrodes. The pulse propagates down the axis to ignite the ignition surface as the propellant regresses. This approach may be combined with either or both of the angled electrodes and conductive/non-conductive additive.

[0018] In an embodiment, the gas generation system is configured as a radial burning rocket motor. An even number of four or more electrodes is spaced radially about a longitudinal axis of the cylindrical rocket fuselage embedded in the electrically operated propellant. Each adjacent pair of said four or more electrodes is angled at greater than 20 degrees and less than 90 degrees with respect to each other such that a cross-section of the propellant between the electrodes increases in area along an axis normal to an ignition surface that regresses radially along the axis away from the longitudinal axis.

[0019] In an example, not claimed, the gas generation system is configured with a conductive coating between the electrically operated propellant and the electrodes. This conductive coating will aid in the efficient transfer of the current and provide for mechanical bonding of the electrically operated propellant to the electrodes.

[0020] In an embodiment, the gas generation system is configured as an airbag deployment system. The electrically operated propellant suitably comprises an ionic perchlorate-based oxidizer that exhibits a self-sustaining threshold of at least 1,000 psi. Combustion of the electrically operated propellant generates pressured gas that is exhausted from the chamber to inflate the airbag. Chamber pressures remain below the self-sustaining threshold such that interruption of the electrical input extinguishes combustion to control the inflation of the airbag.

[0021] The invention is defined in the claims, with preferred embodiments disclosed in the dependent claims. These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

[0022]

FIG. 1 is a plot of current density J along an axis normal to the ignition surface exhibiting a decreasing gradient;

FIG. 2 is a plot of the approximately constant current density J across the contour of the ignition surface;

FIGs. 3a-3c are plots of current density J as the ignition surface regresses along the axis;

FIG. 4 is diagram of the current lines between a pair of parallel wire electrodes embedded in electrically operated propellant;

FIGs. 5a and 5b are different views of the current lines between a center electrode and a cylindrical electrode in a coaxial configuration in which is embedded electrically operated propellant;

FIG. 6 is a diagram of the current lines between a pair of parallel plate electrodes in which one plate is insulated and burns away as the propellant is consumed;

FIG. 7 is a diagram of the current lines between a pair of parallel plate electrodes; FIG. 8 is a diagram of an example of a gas generation system;

FIG. 9 is a diagram of an embodiment of angled electrodes that create a current density gradient along an axis normal to an ignition surface;

FIG. 10 is a diagram of an example, not claimed, in which the electrically operated. propellant includes an additive that creates a current density gradient along an axis normal to an ignition surface;

FIG. 11 is a diagram of an example, not claimed, of segmented parallel electrodes that are switched to propagate an electrical input through the electrically operated propellant;

FIG. 12 is a diagram of a radial burning rocket motor with an even number of angled electrodes positioned radially about the rocket motor;

FIG. 13 is a diagram an end burning rocket motor; and

FIG. 14 is a diagram of a gas generation system using a radial configuration of angled electrodes to inflate an airbag.

DETAILED DESCRIPTION OF THE INVENTION

[0023] The challenge to provide electrical ignition that provides for control of the burn rate and efficient consumption of substantially all of the available propellant, and one that is scalable to combust greater propellant mass to support larger gas generation systems remains.

[0024] Referring now to Figures 1, 2 and 3a-3c, different configurations of electrode structures and electrically operable propellant in a gas generation system must provide an ignition condition at an ignition surface between a pair of electrodes that satisfies three criteria to effectively control burn rate, efficiently consume the available propellant and do so in a manner that is scalable to greater propellant mass.

[0025] First, as shown in Figure 1, a current density J **10** along an axis **12** normal to the ignition surface exhibits a decreasing gradient. The gradient can be produced by, for example, angling and/or segmenting the electrodes and or adding a gradient concentration of a conducting/non-conducting additive to the propellant. The gradient forces combustion to be initiated at the ignition surface having the maximum current density and to regress along the axis normal to the ignition surface in the direction of the decreasing gradient.

[0026] Second, as shown in Figure 2, a current density J **20** across the ignition surface **22** is approximately constant. If this condition is satisfied, the entire ignition surface should ignite. Otherwise, the propellant will only ignite at or near the point of maximum current density J, typically at the surface of one of the electrodes or near the middle of the two electrodes, which hinders the ability to control the burn rate and leaves a lot of propellant unconsumed. To satisfy the second criterion, the contour of the ignition surface is designed and built to match the contour of current lines between the electrodes. To do this, the current lines are calculated for a given electrode configuration and electrically operated propellant. The contour of the ignition surface is then designed to match the contour of the current lines. Contouring the ignition surface can change the current lines. The process may be iterated until any effects are negligible. The contour of the ignition surface as built matches the field lines to the limits of manufacturability. In theory, the design of the contour should exactly match the current lines and the contour as built should exhibit less than a 2% deviation. Satisfying this criterion, substantially all (> 95%) of the ignition surface should be consumed as the ignition surface regresses.

[0027] Third, as shown in Figures 3a-3c, a current density J **30** at the ignition surface **32** exceeds an ignition threshold **34** as the ignition surface regresses at time t = 0+ at initial ignition, t1 and t2. The current density J **30** at the exposed ignition surface must exceed the ignition threshold **34** to combust. The current density J at any cross-section in the bulk of the propellant may or may not exceed ignition threshold **34.** Even if current density J in the bulk exceeds the ignition threshold because the current density J exhibits a decreasing gradient along the axis normal to the ignition surface per the first criterion, ignition will initiate at the exposed ignition surface corresponding to the maximum current density J. As the propellant combusts and the ignition surface regresses, rapidly peeling back layers of the propellant, combustion will continue along the axis. If the current density J in the bulk initially does not exceed the ignition threshold, as the propellant is consumed the total available current flows through less propellant thereby raising the current density J above the ignition threshold at the ignition surface.

[0028] Configurations that satisfy all criteria and particularly the second criterion are critical to scalability, efficiency and controllability. For propellant masses of at least 10 grams, 100 grams, 1,000 grams or more establishing and maintaining the gradient is required to concentrate the available power such that the current density J at the ignition surface exceeds the ignition threshold to sustain ignition. For such propellant masses the spacing between electrodes increases. Matching the contour of the ignition surface to the current lines such that the current density J is approximately constant across the surface is required to ignite and combust substantially all of the ignition surface. If the current density J exhibits even a minimal amount of variance across the ignition surface, for the larger propellant masses and greater electrode spacing, current will be concentrated at the peaks in the current density J and burn only at or near those peaks, typically at the surface of an electrode or a midpoint between the electrodes leaving a lot of propellant unconsumed. If the criteria are satisfied, substantially all of the available propellant, > 95%, should be consumed. If combustion is interrupted, that means at least 95% of the available mass up to the point of extinguishment.

[0029] Let us first consider the performance and limitations of known ignition systems and electrode configurations for electrically operated propellants.

[0030] As shown in Figure 4, a pair of parallel wires **40** and **42** are embedded in an electrically operated propellant **44.** Current flows from the positive electrode, wire **42,** to the negative electrode, wire **40,** along current lines **46.** The spacing of current lines **46** dictates the current density J. The closer the current lines **46,** the higher the current density J. In this configuration, the current density J is the highest at wire **40.** The current density J is uniform along an axis into the propellant parallel to the wires. Testing has demonstrated that application of an electrical input to the wires creates an ignition condition in which the propellant at the surface of wire **40** is ignited and the amount of propellant that combusts is very small. The propellant burns for only a small distance away from wire **40** and extinguishes. The parallel wires provide neither the current density J gradient along the axis nor the approximately constant current density J across an ignition surface required to ignite an ignition surface between the wires and cause the ignition surface to regress along the axis.

[0031] As shown in Figures 5a and 5b, a coaxial electrode configuration includes a cylindrical positive electrode **50** and a negative electrode **52** along the axis **54** of the positive electrode. Current flows from positive electrode **50** to negative electrode **52** along current lines **56.** The current density is a maximum at the concentration of current lines **56** at negative electrode **52.** The negative electrode **52** is provide with an insulative sleeve **58** that serves to further concentrate the current lines **56** at an exposed end **60** of negative electrode **52.** Testing has demonstrated that application of an electrical input to the coaxial electrode configuration creates an ignition condition in which the propellant at an ignition surface **62** at end **60** ignites. This burns back the insulative sleeve **58** allowing ignition surface **62** to regress along axis **54.** However, the testing demonstrated that this only holds for very small amounts of propellant, less than 1 gram, and very small electrodes, about 1/8" in diameter for the coaxial configuration. If the diameter of the coaxial electrode is scaled up to accommodate larger propellant mass, the propellant ignites only at or near the center negative electrode **52** leaving much of the propellant unconsumed.

[0032] The coaxial electrode structure creates a current density J that is maximum at the center and falls off as 1/radius. This non-uniformity is further exacerbated by the insulative sleeve that concentrates the field lines at the center. For coaxial electrode structures on the order of 1/8" in diameter, the electrical input is sufficient to overcome this non-uniformity and ignite the entire ignition surface. However as the diameter increases the current density J is too low to ignite and combustion is limited to a small area around the center electrode.

[0033] As shown in Figure 6, a parallel plate electrode configuration includes a positive plate electrode **70** and a negative plate electrode **72** with a bare end **74** and insulation **76.** Similar to the coaxial configuration, the insulation concentrates current lines **78** at the bare end **74** of negative plate electrode **72.** Testing has demonstrated that application of an electrical input to the parallel plate configuration creates an ignition condition in which the propellant at an ignition surface **80** at end **74** ignites. This burns back insulation **76** allowing ignition surface **80** to regress along an axis **82** between the plates. However, the testing demonstrated that this only holds for very small amounts of propellant, less than 1 gram, and very small electrodes spaces, about 1/8" between the parallel plates. If the spacing is scaled up to accommodate larger propellant mass, the propellant ignites only at or near the insulated negative plate electrode **72** leaving much of the propellant unconsumed.

[0034] The parallel plate structure itself would creates a current density J was uniform across the ignition surface. However, the concentration of the current lines at the bare end of the negative plate electrode **72** produces a non-uniformity in the current density J, which peaks at the negative plate electrode **72** and falls off towards positive plate electrode **70.** For small structures, the electrical input is sufficient to overcome this non-uniformity and ignite the entire ignition surface. However as the plate spacing increases the current density J is too low to ignite and combustion is limited to a small area near negative plate electrode **72.**

[0035] As shown in Figure 7, a parallel plate electrode configuration includes a positive plate electrode **90** and a negative plate electrode **92.** Because neither plate is insulated, current lines **94** match the contour of a desired ignition surface such that the current density J is constant across the ignition surface. However, the current density J is also constant throughout the bulk of the electrically operable propellant **96.** This requires a lot of current, i.e., power, to raise the current density J above the ignition threshold to initiate combustion. Furthermore, if the power is sufficient to exceed the ignition threshold testing has demonstrated that the bulk of the electrically operated propellant will all ignite at once. This configuration, without the insulation, does not create a preferential ignition surface to ignite and regress in a controlled manner along an axis between the plates.

[0036] None of the known electrode configurations satisfy all three criteria for ignition of an electrically operated propellant.

[0037] The present invention provides different configurations of electrode structures and electrically operable propellant in a gas generation system that provide an ignition condition at an ignition surface between a pair of electrodes that satisfies the three criteria of current density J that exhibits a decreasing gradient along an axis normal to an ignition surface, is constant across the ignition surface and exceeds an ignition threshold at the ignition surface. These configurations improve burn rate control and consumption of the available propellant and are scalable to greater propellant mass to support larger gas generation systems.

[0038] These configurations are useful for all varieties of electrical operated propellants. The configurations may be used with electrical operated propellants that exhibit no ability to be extinguished, propellants with a HAN-based oxidizer that exhibit a low self-sustaining threshold of about 150 psi, propellants with a perchlorate-based oxidizer that exhibit self-sustaining thresholds above 500, 1,000, 1,500 or event 2,000 psi. U.S. Patent 8,950,329 which details the formulation of the perchlorate-based electrically operated propellant is hereby incorporated by reference. The gas generation systems may be configured to simply burn the entire electrically operated propellant to extinction at a given burn rate, to control the burn rate and burn to extinction, to turn the combustion on and off, and back on again.

[0039] Without loss of generality, an embodiment of a gas generation system with an electrically operated propellant that can be throttled and turned on/off/on as long as the chamber pressure remains below the self-sustaining threshold pressure will be presented. An exemplary electrically operated propellant includes a metal-based fuel of approximate 5 to 30 percent of the mass of the propellant, a liquid perchlorate-based ionic oxidizer of approximately 50 to 90 percent of the mass and a binder of approximately 10 to 30 percent of the mass.

[0040] Referring now to Figure 8, a gas generation system **100,** not claimed, includes a gas generator **102,** a controller **104** and a power source **106** such as a battery, generator or the like. Gas generator **102** is usable to provide a source of pressurized gas for a rocket motor, attitude and control systems, gas compressors, ignition systems, airbag inflation systems and the like.

[0041] Gas generator **102** includes a combustion chamber **108** having an electrically operated propellant **110** positioned therein. Two or more electrodes **112** extend into the electrically operated propellant **110** within the combustion chamber **112.** A nozzle **114** is coupled to combustion chamber **112.** Electrically operated propellant **110** includes a formulation that allows for the ignition and extinguishing of the propellant in a variety of conditions according to the application (and interruption of the application) of electricity through the electrodes **112.** For instance, the electrically operated propellant **110** is configured to ignite with the application of voltage across the electrodes **112.** Conversely, the electrically operated propellant **110** is extinguished with the interruption of the voltage at a range of chamber pressures (e.g., from 500 psi to 2000 psi) less than the self-sustaining threshold pressure. The two or more electrodes **112** and electrically operated propellant **110** are configured to produce an ignition condition that satisfies the three criteria. Ignition and combustion of the electrically operated propellant **110** produces elevated chamber pressures. Gas is exhausted through nozzle **114** to generate high pressure/high velocity gas for a particular application.

[0042] Controller **104** is shown as including in one example a generation module **120** (e.g., a flight module for a rocket or airbag inflation module for a vehicle). The generation module **120** is coupled with a voltage control module **122** and a power measurement module **124.** In one example, the generation module **120** is a flight module, and the flight module is configured to control the amount of thrust provided as part of a rocket motor. For instance, as ignition, extinguishing and throttling of thrust output from the gas generator **102** is desired, the flight module is configured to provide this control by way of management of the electrical output to the gas generator through control of the voltage control module **122.**

[0043] The voltage control module **122** is coupled along the electrical circuit between the power source **106** and the gas generator **102.** The voltage control module **122** is in one example coupled with the power measurement module **124.** The power measurement module is configured to measure the output of the power source and thereby facilitate control and administration of the appropriate amount of electricity such as voltage, current or the like to the gas generator through the voltage control module.

[0044] In an example, the generation module **120** includes one or more of an ignition module **130** to control the application of the electrical input to the electrically operated propellant via the electrodes, an extinguishing module **132** to interrupt the application of the electrical input to extinguish combustion, a throttling module **134**

to vary the electrical input to increase or decrease the burn rate and a pressure monitoring module **134** to measure the chamber pressure to provide feedback to the other modulates to control ignition, extinguishment and throttling. Each of these modules controls various corresponding functions of the gas generator **102.**

[0045] Referring to Figure 9, an embodiment of an electrode configuration for a gas generator comprises a pair of plate electrodes **200** and **202** that are angled between 20 and 90 degrees, and more typically between 20 and 60 degrees, with respect to each other such that a cross section **204** of an electrically operated propellant **206** increases in area along an axis **208** normal to an ignition surface **210.** The increasing diameter of cross-section **204** creates a gradient in the current density J (in a given cross-section) that decreases along the axis. The applied electrical signal, conductivity of the electrically operated propellant and the angle of the pair of electrodes establish a current density J at the ignition surface that exceeds an ignition threshold. The ignition surface is contoured to match the contour of current lines **212** between the plate electrodes. Because the plate electrodes are "angled" (not parallel), the contour that matches the current lines is not flat. The amount of curvature is dictated by the angle between the plates. The current density J at a narrow end **214** will be the highest and will decrease along axis **208** to a lowest value at a wide end **216.** Upon application of an electrical input between the pair of plate electrodes **200** and **202,** ignition surface **210** at narrow end **214** will ignite across substantially all of the surface and regress along axis **208** normal to the ignition surface. Unless the electrical signal is interrupted to extinguish combustion, combustion will continue along the axis to burn substantially all of the propellant.

[0046] Referring to Figure 10, an example, not claimed, of an electrode configuration for a gas generator comprises a pair of parallel plate electrodes **230** and **232** on either side of an electrically operated propellant **234.** A conducting or non-conductive additive **236** is added to the electrically operated propellant. The additive **236** has a gradient concentration along an axis **238** normal to an ignition surface **240,** which modifies the conductivity of the propellant to have a decreasing gradient along the axis, which in turn produces a current density J with a decreasing gradient along the axis. A conducting additive would have maximum concentration at the ignition surface decreasing along the axis. A non-conductive additive (as shown) would have a minimum concentration at the ignition surface increasing along the axis. The current lines **242** between the parallel plate electrodes **230** and **232** are normal to axis **238** and evenly spaced. Accordingly, the ignition surface has a flat contour to match the current lines. Upon application of an electrical input between the pair of plate electrodes **230** and **232,** ignition surface **240** will ignite across substantially all of the surface at the maximum current density J and regress along axis **238** normal to the ignition surface. Unless the electrical signal is interrupted to extinguish combustion, combustion will continue along the axis to burn substantially all of the propellant.

[0047] Referring now to Figure 11, an example, not claimed, of an electrode configuration for a gas generator comprises a pair of parallel plate electrodes **250** and **252** on either side of an electrically operated propellant **253.** Each of the electrodes **250** and **252** comprises a plurality of sub-electrodes **254a, 254b,** .... and **256a, 256b,** ..... A network of relay **258** and switches **260** selectively activate one pair of sub-electrodes **254a/256a, 254b/256b** ... at a time to propagate the electrical signal, supplied by voltage source 257, along an axis **258** normal to an ignition surface **261.** The decreasing gradient of current density J constitutes a pulse **262** at the activated pair of sub-electrodes followed by a null at the following unactivated pairs of sub-electrodes. The pulse **262** propagates down the axis **258** to ignite the ignition surface **261** as the propellant regresses. The same concept of using segmented electrodes and a network of relays and switches to propagate a pulse through the electrically operated propellant may be applied to angled electrodes or concentric electrodes.

[0048] Any two or more of the angled electrodes, non-conducting/conducting additive to the electrically operated propellant and segmented electrodes may be combined. Other configurations of electrode structures and propellant conductivity may be envisioned that satisfy the three criteria for efficient, controllable and scalable combustion of the electrically operated propellant.

[0049] Referring now to Figure 12, an embodiment of a radial burning rocket motor **300** comprises an even number of four or more electrodes **302** is spaced radially about a longitudinal axis **304** of a cylindrical rocket fuselage **306** and embedded in a electrically operable propellant **308.** Each adjacent pair of said four or more the electrodes is angled at greater than 20 degrees and less than 90 degrees with respect to each other such that a cross-section **310** of the propellant between the electrodes increases in diameter along an axis **312** normal to an ignition surface **314** that regresses radially along the axis **312** away from the longitudinal axis **304.** Field lines **316** extend from the positive electrodes to the negative electrodes. The resulting pressurized gas is exhausted through a nozzle to produce thrust.

[0050] Referring now to Figure 13, an example, not claimed, of an end-burning rocket motor **400** comprises concentric circular electrodes **402** and **404** about a longitudinal axis **406** of a cylindrical rocket fuselage **408,** which extend the length of an electrically operable propellant **410** embedded between the inner and outer circular electrodes. Electrically operable propellant **408** is provided with an additive that varies its conductance to create a gradient current density that is a maximum at an ignition surface **412** at an end **414** of the rocket motor. Application of an electrical signal to the concentric circular electrodes ignites ignition surface **412** only at end **414.** The ignition surface **412** burns and regresses axially along longitudinal axis **404** to consume the electrically operable propellant. The resulting pressurized gas is exhausted through a nozzle to produce thrust. Alternately, the electrodes may be configured as parallel plates with a rectangular cross-section.

[0051] Referring now to Figure 14, an embodiment of an airbag inflation system **500** includes a gas generation system **502** that uses an electrically operated propellant **508** within a combustion chamber **504** configured to pressurize the chamber and exhaust high-pressure gas through an opening **512** to inflate an airbag **513.** Opening **512** may be or may not be formed as a nozzle. The electrically operated propellant **508** includes a formulation (e.g., a perchlorate-based ionic oxidizer) that allows for the ignition and extinguishing of the propellant in a variety of conditions according to the application (and interruption of the application) of electricity a chamber pressures below a self-sustaining threshold pressure of at least 1,000 psi.

[0052] An electrode structure and electrically operated propellant are configured to satisfy the three criteria. In an exemplary embodiment, the ignition system suitably comprising an even number of four or more electrodes **510** that extend into electrically operated propellant **508** within the combustion chamber **504.** Electrodes **510** are spaced radially about a longitudinal axis **515** and embedded in an electrically operable propellant **514.** Each adjacent pair of said four or more the electrodes is angled at greater than 20 degrees and less than 90 degrees with respect to each other such that a cross-section of the propellant between the electrodes increases in diameter along an axis normal to an ignition surface that regresses radially along the axis away from the longitudinal axis **515.** The electrodes alternate as + and - electrodes. The + electrodes are connected to an external positive electrode **522** and the - electrodes are connected to an external negative **524** for connection to a power supply.

[0053] To inflate airbag **513,** an electrical input is applied through positive and negative electrodes **522** and **524** to alternating electrodes **510** to produce a current density J at the interior ignition surface **520** between each pair of electrodes **510** that exceeds an ignition threshold. Each ignition surface ignites and regresses along axis normal to the ignition surface. The combustion of the electrically operated propellant generates pressured gas in combustion chamber **504.** Pressure levels in the chamber reaching more than 500 psi but never more than the self-sustaining threshold pressure. Pressurized gas I the chamber is exhausted through opening **512** to inflate airbag **513.** The electrical input is varied to vary a rate of combustion, hence varying the pressure levels in the chambers to control a pressure profile of the airbag. The electrical signal is interrupted to extinguish combustion of the propellant to control a total pressure impulse delivered to the airbag. Combustion may be turned on and off by application and interruption of the electrical signal

[0054] While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art.

Claims

1. A gas generation system (300), comprising:

    a combustion chamber (504);
    an electrically operated propellant (308) within the combustion chamber; and
    characterised in that the gas generation system further comprises:

        an even number of four or more alternating + and - electrodes (302) configured for coupling with an electrical power source, said electrical power source configured to apply an electrical input across the electrodes, the gas generation system configured to create an ignition condition in which (a) a current density (J) through the propellant between each adjacent pair of electrodes on an ignition surface (314) exhibits a decreasing gradient along an axis normal to the ignition surface, (b) a contour of the ignition surface approximately matches a contour of current lines between the electrodes such that current density (**J**) is approximately constant across the ignition surface and (c) the current density (**J**) at the ignition surface exceeds an ignition threshold as approximately all of ignition surface burns and regresses along the axis, and wherein
        the even number of four or more said electrodes are spaced radially about a longitudinal axis (304) and embedded in said electrically operated propellant, each adjacent pair of said four or more electrodes being angled at greater than 20 degrees and less than 90 degrees with respect to each other such that a cross-section of the propellant between the electrodes increases in diameter along an axis (312) normal to an ignition surface that regresses radially along the axis (312) away from the longitudinal axis (304).

2. The gas generation system of claim 1, wherein the contour of the ignition surface approximately matches the contour of current lines between the electrodes to within 5% such that current density (**J**) is approximately constant across the ignition surface to within 5%.

3. The gas generation system of claim 1, wherein at least 95% of the ignition surface burns as the surface regresses radially along the axis away from the longitudinal axis.

4. The gas generation system of claim 1, wherein the system comprises at least 10 grams of the electrically operated propellant that is consumed as the ignition surface burns and regresses radially along the axis away from the longitudinal axis.

5. The gas generation system of claim 1, wherein the system comprises at least 100 grams of the electrically operated propellant that is consumed as the ignition surface burns and regresses radially along the axis away from the longitudinal axis.

6. The gas generation system of claim 1, wherein the system comprises at least 1,000 grams of the electrically operated propellant that is consumed as the ignition surface burns and regresses radially along the axis away from the longitudinal axis.

7. The gas generation system of claim 1, further comprising a conducting or non-conductive additive in the electrically operated propellant having a gradient concentration along the axis normal to the ignition surface.

8. The gas generation system of claim 1, wherein the electrically operated propellant comprises an ionic perchlorate-based oxidizer such that the propellant has a self-sustaining threshold pressure of at least 3447.38 KPa (500 psi) at which the propellant once ignited by the electrical input cannot be extinguished and below which the propellant can be extinguished by interruption of the electrical input.

9. The gas generation system of claim 8, wherein the self-sustaining threshold pressure is at least 6894,76 KPa (1,000 psi).

10. The gas generation system of claim 1, further comprising:

    a cylindrical rocket fuselage (306); and wherein the even number of four or more said electrodes are spaced radially about a longitudinal axis of the cylindrical rocket fuselage.

11. The gas generation system of claim 1, further comprising:
an airbag (513) coupled to the combustion chamber, wherein the combustion of the electrically operated propellant generates pressured gas that is exhausted from the chamber to inflate the airbag.

Patentansprüche

1. Gasgeneratorsystem (300), Folgendes umfassend:

    eine Verbrennungskammer (504);
    einen elektrisch betätigten Treibstoff (308) in der Verbrennungskammer; und
    dadurch gekennzeichnet, dass das Gasgeneratorsystem weiterhin Folgendes umfasst:

        eine gerade Anzahl von mindestens vier alternierenden + und - Elektroden (302), die zum Verbinden mit einer elektrischen Stromquelle eingerichtet sind, wobei die elektrische Stromquelle eingerichtet ist, um eine elektrische Eingangsleistung an den Elektroden anzulegen, das Gasgeneratorsystem eingerichtet ist, um einen Zündzustand zu erzeugen, bei dem (a) eine Stromdichte (J) durch den Treibstoff zwischen jedem benachbarten Elektrodenpaar auf einer Zündoberfläche (314) einen sich vermindernden Gradienten entlang einer Achse senkrecht zu der Zündoberfläche zeigt, (b) eine Kontur der Zündoberfläche ungefähr mit einer Kontur von Stromstrichen zwischen den Elektroden übereinstimmt, so dass eine Stromdichte (J) über die Zündoberfläche ungefähr konstant ist, und (c) die Stromdichte (J) an der Zündoberfläche einen Zündschwellenwert überschreitet, während ungefähr die gesamte Zündoberfläche brennt und entlang der Achse zurückläuft, und wobei
        die gerade Anzahl von mindestens vier der Elektroden radial um eine Längsachse (304) beabstandet sind und in dem elektrisch betätigten Treibstoff eingebettet sind, wobei jedes benachbarte Paar der mindestens vier Elektroden um mehr als 20 Grad und um weniger als 90 Grad zueinander gewinkelt sind, so dass sich ein Querschnitt des Treibstoffs zwischen den Elektroden entlang einer Achse (312) senkrecht zu einer Zündoberfläche, die radial entlang der Achse (312) weg von der Längsachse (304) zurückläuft, im Durchmesser erhöht.

2. Gasgeneratorsystem nach Anspruch 1, wobei die Kontur der Zündoberfläche ungefähr mit der Kontur von Stromstrichen zwischen den Elektroden innerhalb von 5 % derartig übereinstimmt, dass eine Stromdichte (J) über die Zündoberfläche innerhalb von 5 % ungefähr konstant ist.

3. Gasgeneratorsystem nach Anspruch 1, wobei mindestens 95 % der Zündoberfläche brennt, während die Oberfläche radial entlang der Achse weg von der Längsachse zurückläuft.

4. Gasgeneratorsystem nach Anspruch 1, wobei das System mindestens 10 Gramm des elektrisch betätigten Treibstoffs umfasst, der verbraucht wird, wäh-

rend die Zündoberfläche brennt und radial entlang der Achse weg von der Längsachse zurückläuft.

5. Gasgeneratorsystem nach Anspruch 1, wobei das System mindestens 100 Gramm des elektrisch betätigten Treibstoffs umfasst, der verbraucht wird, während die Zündoberfläche brennt und radial entlang der Achse weg von der Längsachse zurückläuft.

6. Gasgeneratorsystem nach Anspruch 1, wobei das System mindestens 1.000 Gramm des elektrisch betätigten Treibstoffs umfasst, der verbraucht wird, während die Zündoberfläche brennt und radial entlang der Achse weg von der Längsachse zurückläuft.

7. Gasgeneratorsystem nach Anspruch 1, weiterhin einen leitenden oder nichtleitenden Zusatzstoff in dem elektrisch betätigten Treibstoff mit einer Gradientenkonzentration entlang der Achse senkrecht zu der Zündoberfläche umfassend.

8. Gasgeneratorsystem nach Anspruch 1, wobei der elektrisch betätigte Treibstoff ein ionisches Perchlorat-basiertes Oxidiermittel umfasst, so dass der Treibstoff einen Selbsterhaltungsschwellendruck von mindestens 3447,38 kPa (500 psi) aufweist, bei dem der einmal durch die elektrische Eingangsleistung gezündete Treibstoff nicht gelöscht werden kann und unter dem der Treibstoff durch Unterbrechung der elektrischen Eingangsleistung gelöscht werden kann.

9. Gasgeneratorsystem nach Anspruch 8, wobei der Selbsterhaltungsschwellendruck mindestens 6894,76 kPa (1.000 psi) ist.

10. Gasgeneratorsystem nach Anspruch 1, weiterhin Folgendes umfassend:

einen zylindrischen Raketenrumpf (306); und wobei
die gerade Anzahl von mindestens vier der Elektroden radial um eine Längsachse des zylindrischen Raketenrumpfs beabstandet sind.

11. Gasgeneratorsystem nach Anspruch 1, weiterhin Folgendes umfassend:
einen Prallsack (513), der mit der Verbrennungskammer verbunden ist, wobei die Verbrennung des elektrisch betriebenen Treibstoffs Druckgas erzeugt, das aus der Kammer ausgestoßen wird, um den Prallsack aufzublasen.

Revendications

1. Système de génération de gaz (300), comprenant :

une chambre de combustion (504) ;
un propulseur à commande électrique (308) à l'intérieur de la chambre de combustion ; et
caractérisé en ce que le système de génération de gaz comprend en outre :

un nombre pair de quatre ou plus de quatre électrodes + et - alternées (302) configurées pour être couplées à une source d'énergie électrique, ladite source d'énergie électrique étant configurée pour appliquer une entrée électrique entre les électrodes, le système de génération de gaz étant configuré pour créer une condition d'allumage dans laquelle (a) une densité de courant (J) à travers le propulseur entre chaque paire adjacente d'électrodes sur une surface d'allumage (314) présente un gradient décroissant le long d'un axe normal à la surface d'allumage, (b) un contour de la surface d'allumage correspond approximativement à un contour des lignes de courant entre les électrodes de sorte que la densité de courant (J) est approximativement constante sur la surface d'allumage et (c) la densité de courant (J) au niveau de la surface d'allumage dépasse un seuil d'allumage lorsqu'approximativement toute la surface d'allumage se consume et régresse le long de l'axe, et
le nombre pair de quatre ou plus de quatre desdites électrodes étant espacées radialement autour d'un axe longitudinal (304) et intégrées dans ledit propulseur à commande électrique, chaque paire adjacente desdites quatre ou plus de quatre électrodes étant inclinées à plus de 20 degrés et moins de 90 degrés les unes par rapport aux autres de sorte qu'une section transversale du propulseur entre les électrodes augmente en diamètre le long d'un axe (312) normal à une surface d'allumage qui régresse radialement le long de l'axe (312) en s'éloignant de l'axe longitudinal (304).

2. Système de génération de gaz selon la revendication 1, le contour de la surface d'allumage correspondant approximativement au contour des lignes de courant entre les électrodes à 5 % près, de sorte que la densité de courant (J) est approximativement constante à travers la surface d'allumage à 5 % près.

3. Système de génération de gaz selon la revendication 1, au moins 95 % de la surface d'allumage se consumant lorsque la surface régresse radialement le long de l'axe en s'éloignant de l'axe longitudinal.

4. Système de génération de gaz selon la revendication

1, le système comprenant au moins 10 grammes de propulseur à commande électrique qui est consommé lorsque la surface d'allumage se consume et régresse radialement le long de l'axe en s'éloignant de l'axe longitudinal.

5. Système de génération de gaz selon la revendication 1, le système comprenant au moins 100 grammes de propulseur à commande électrique qui est consommé lorsque la surface d'allumage se consume et régresse radialement le long de l'axe en s'éloignant de l'axe longitudinal.

6. Système de génération de gaz selon la revendication 1, le système comprenant au moins 1000 grammes de propulseur à commande électrique qui sont consommés lorsque la surface d'allumage se consume et régresse radialement le long de l'axe en s'éloignant de l'axe longitudinal.

7. Système de génération de gaz selon la revendication 1, comprenant en outre un additif conducteur ou non conducteur dans le propulseur à commande électrique ayant un gradient de concentration le long de l'axe normal à la surface d'allumage.

8. Système de génération de gaz selon la revendication 1, le propulseur à commande électrique comprenant un oxydant à base de perchlorate ionique de telle sorte que le propulseur a une pression seuil auto-entretenue d'au moins 3447,38 kPa (500 psi) à laquelle le propulseur, une fois allumé par l'entrée électrique, ne peut pas être éteint et en dessous de laquelle le propulseur peut être éteint par interruption de l'entrée électrique.

9. Système de génération de gaz selon la revendication 8, la pression seuil auto-entretenue étant d'au moins 6894,76 kPa (1000 psi).

10. Système de génération de gaz selon la revendication 1, comprenant en outre ;

un fuselage de fusée cylindrique (306) ; et
le nombre pair de quatre ou plus de quatre desdites électrodes étant espacées radialement autour d'un axe longitudinal du fuselage de fusée cylindrique.

11. Système de génération de gaz selon la revendication 1, comprenant en outre :
un coussin gonflable (513) couplé à la chambre de combustion, la combustion du propulseur à commande électrique générant un gaz sous pression qui est évacué de la chambre pour gonfler le coussin gonflable.

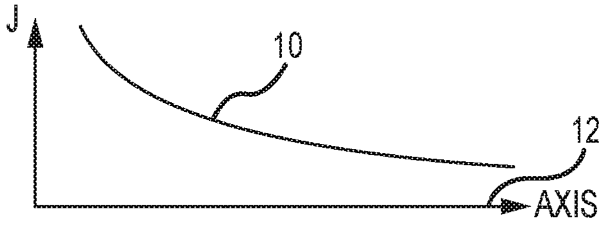

FIG.1

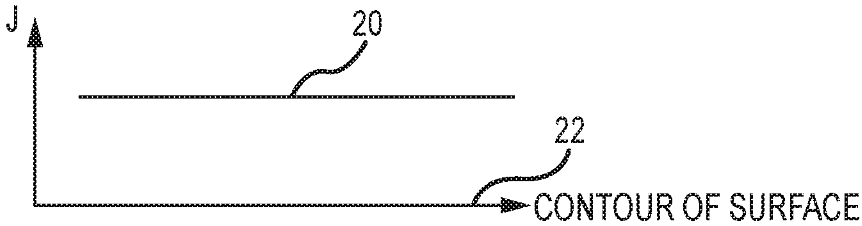

FIG.2

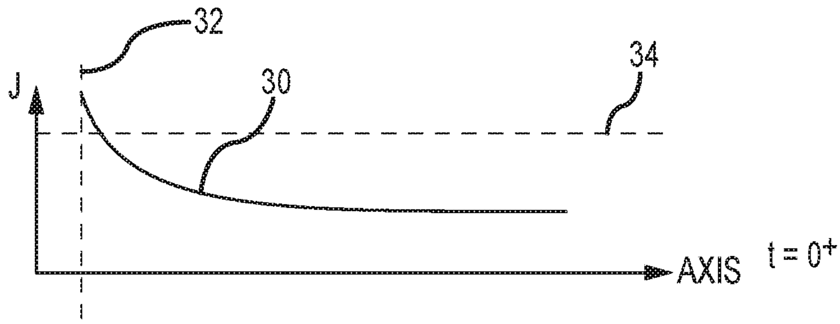

FIG.3a

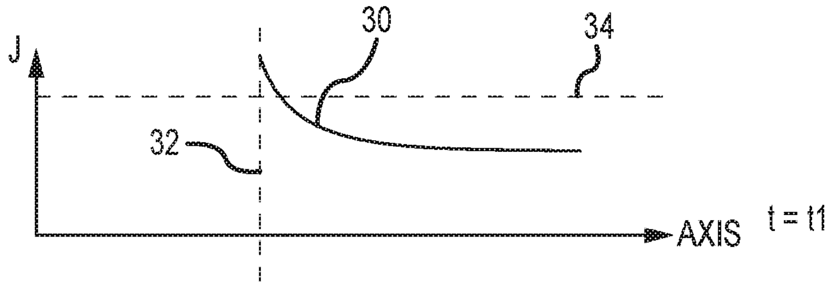

FIG.3b

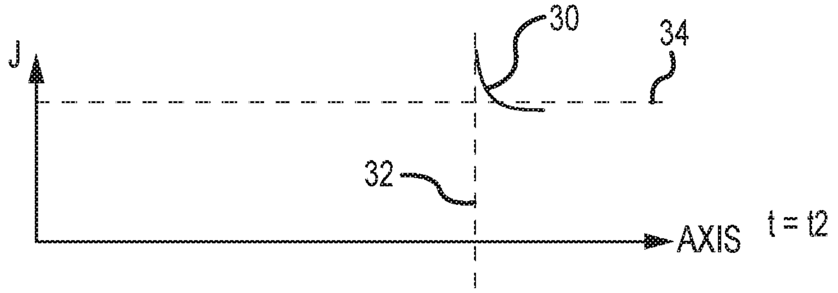

FIG.3c

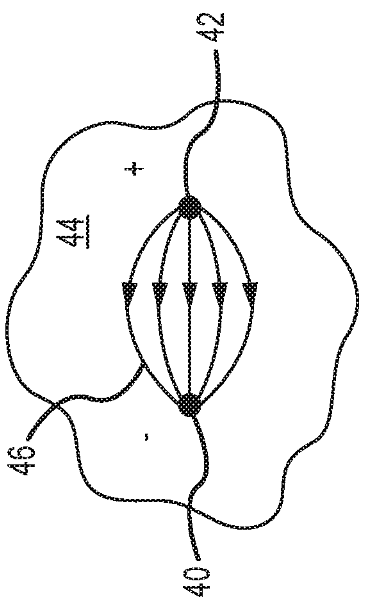

FIG.4

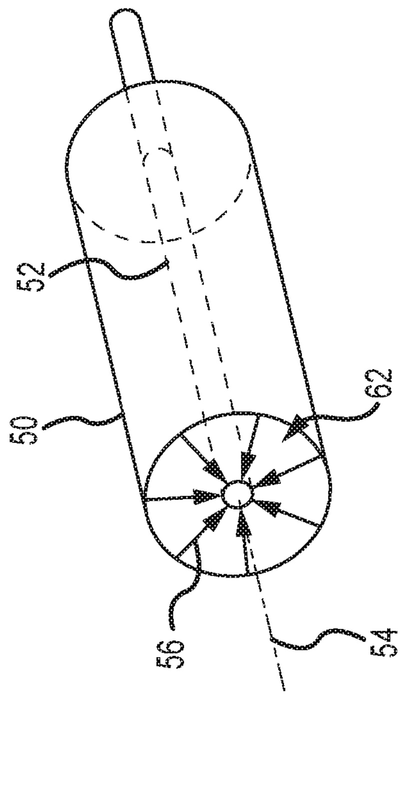

FIG.5a

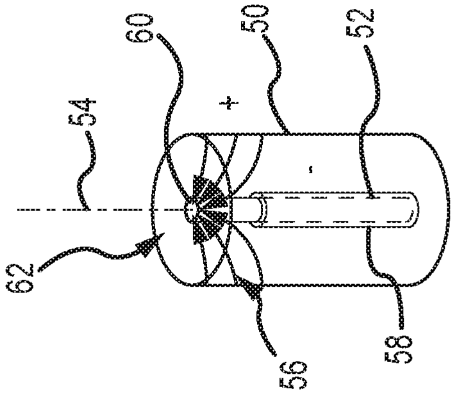

FIG.5b

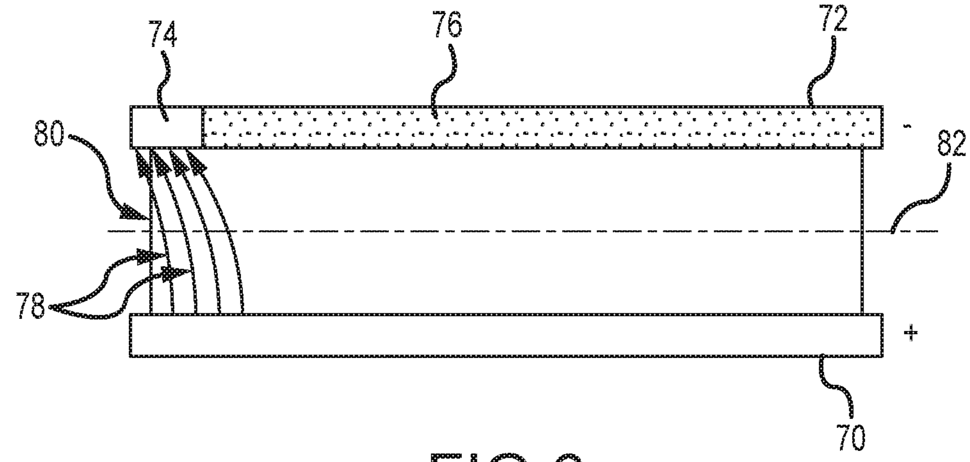

FIG.6

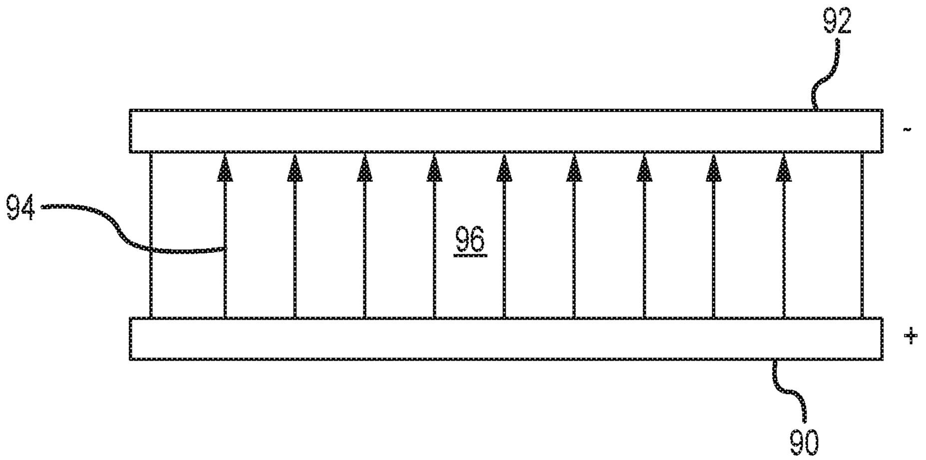

FIG.7

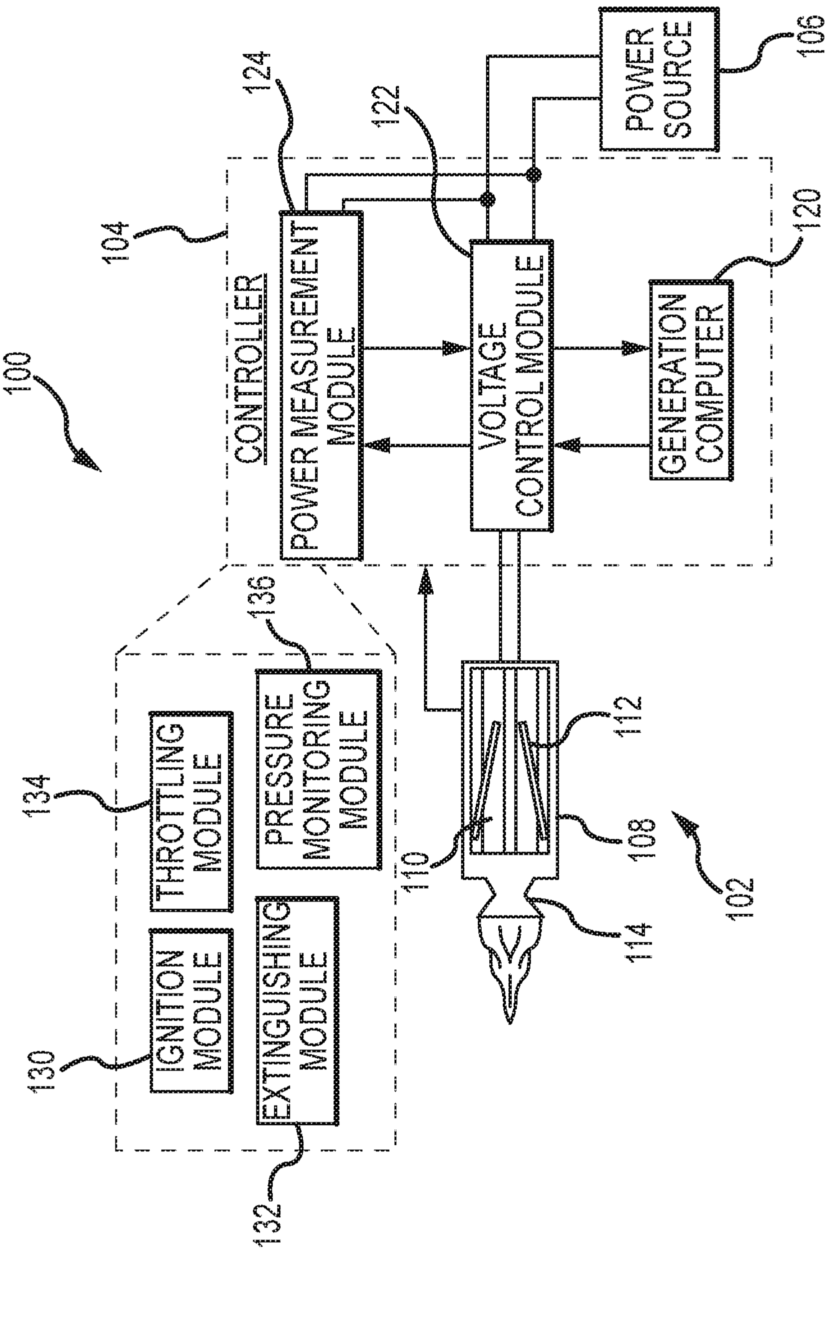
100
104
CONTROLLER
124
POWER MEASUREMENT MODULE
122
VOLTAGE CONTROL MODULE
120
GENERATION COMPUTER
POWER SOURCE
106
136
PRESSURE MONITORING MODULE
134
THROTTLING MODULE
130
IGNITION MODULE
EXTINGUISHING MODULE
132
112
110
108
114
102

FIG.8

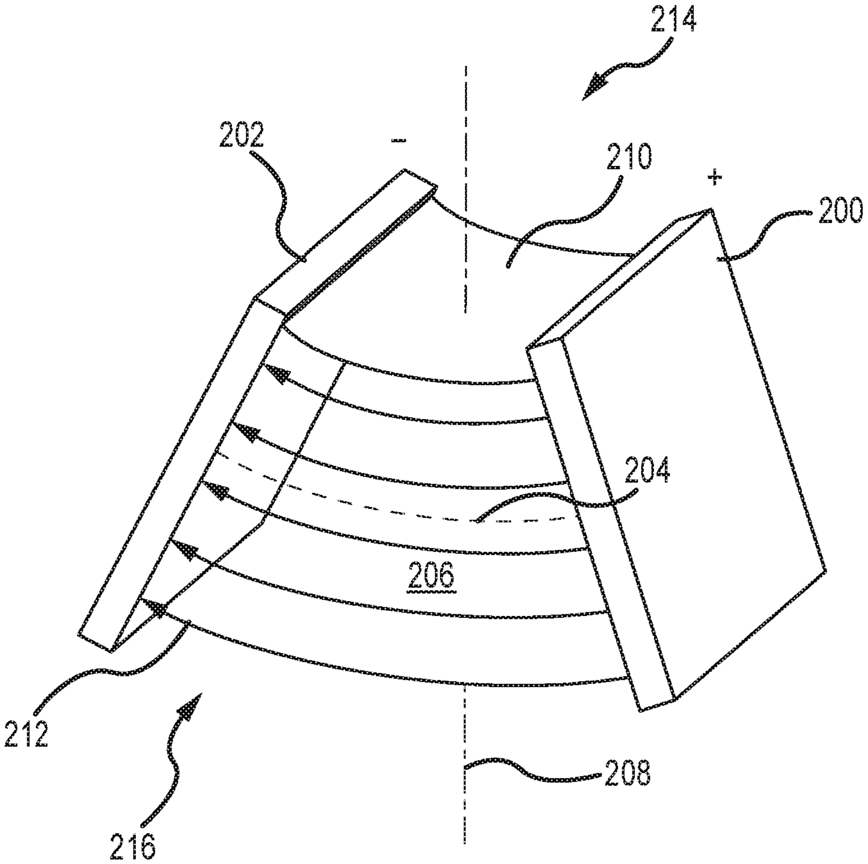

FIG.9

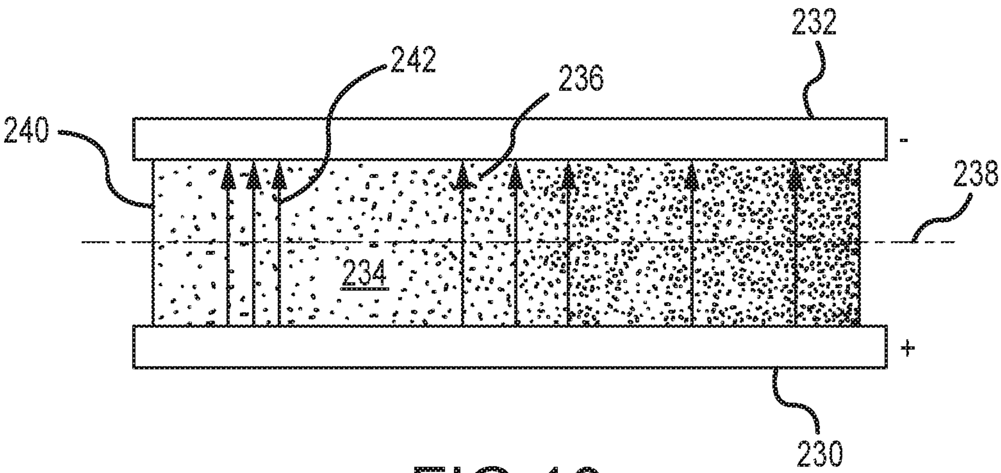

FIG.10

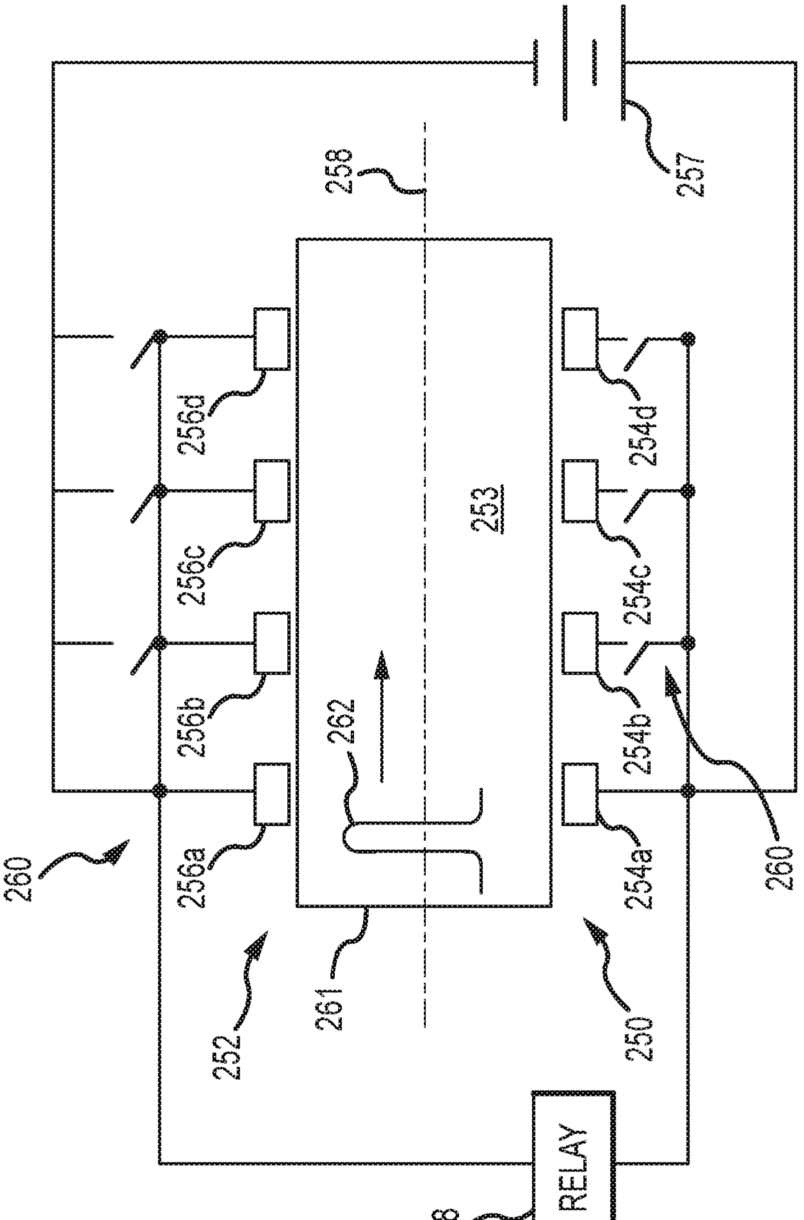
258
257
256d
256c
256b
256a
253
262
261
260
252
250
254a
254b
254c
254d
260
RELAY
258

FIG. 11

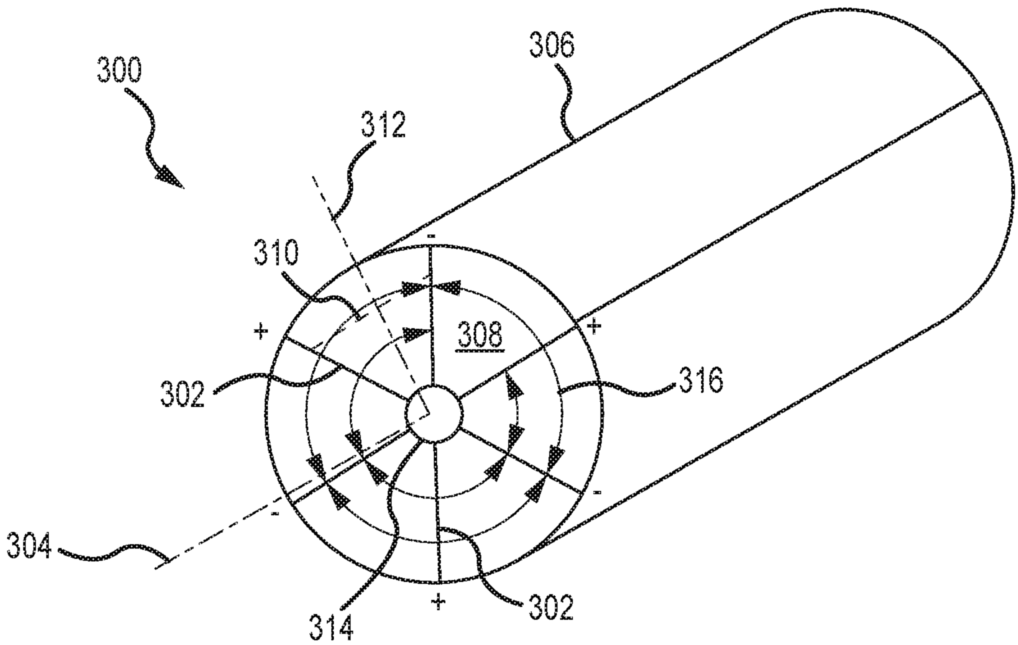

FIG.12

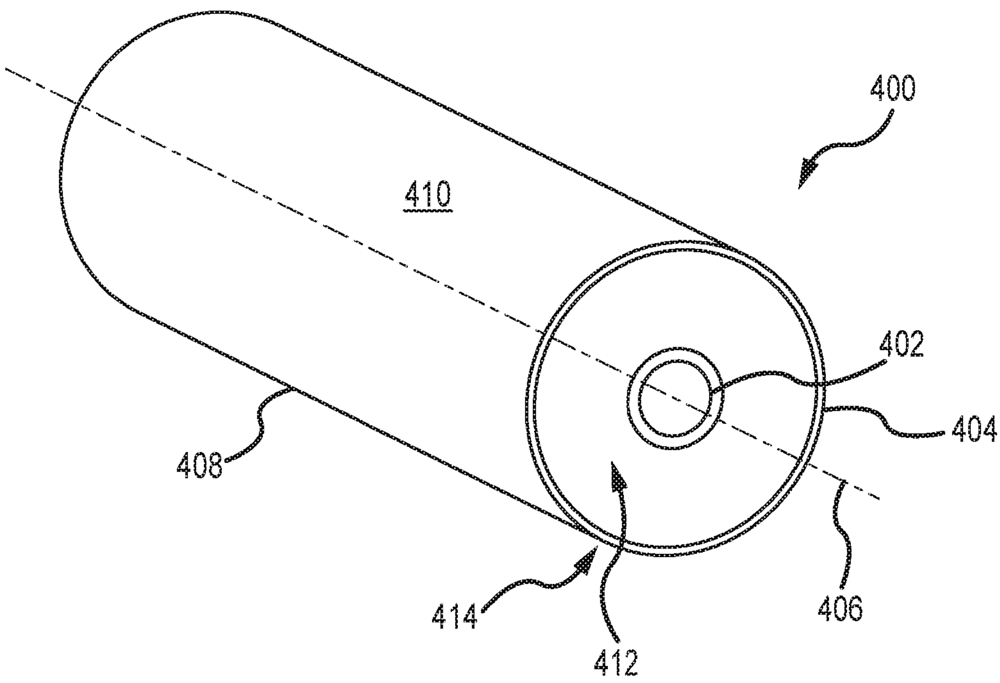

FIG.13

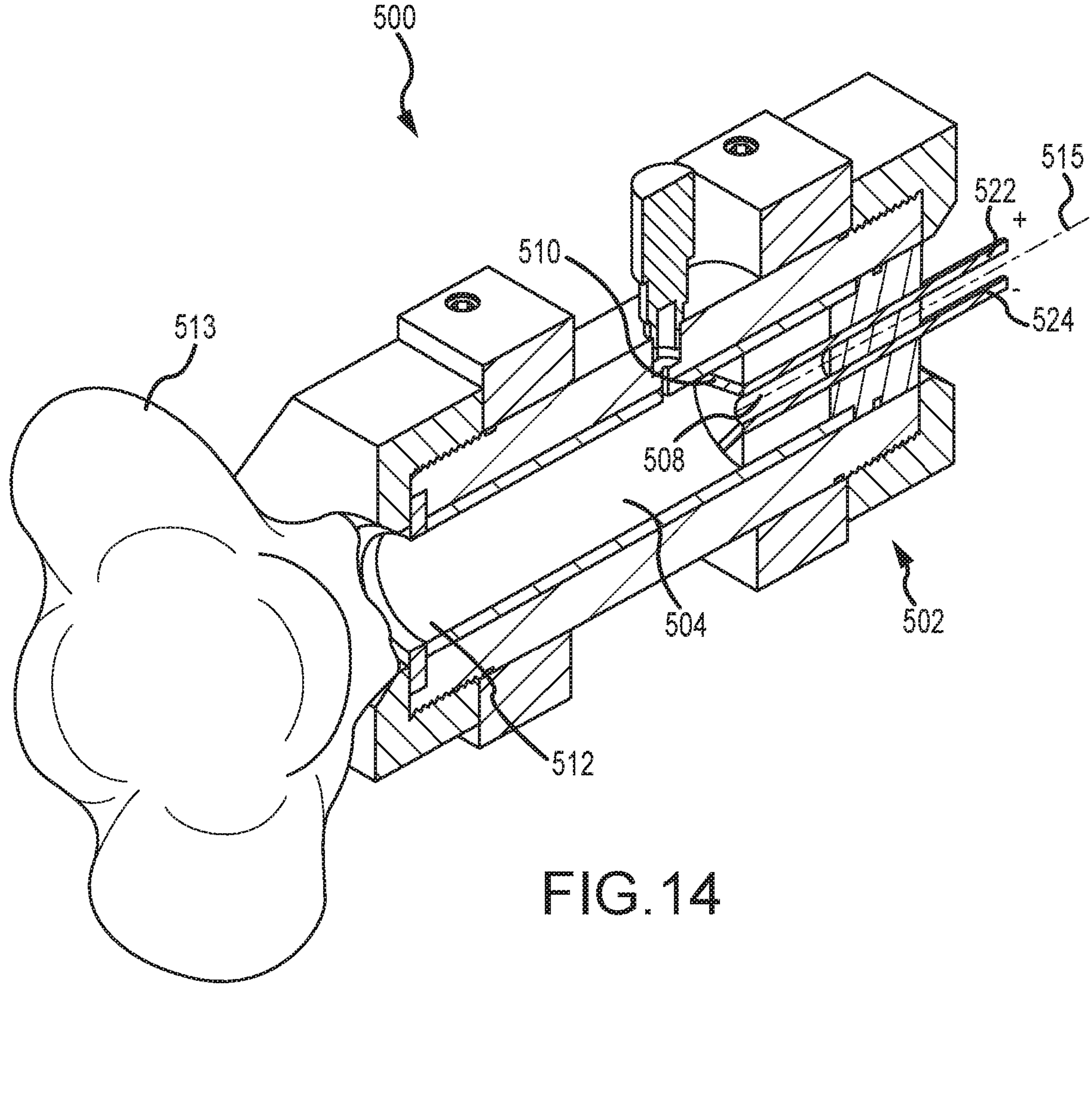

FIG.14

REFERENCES CITED IN THE DESCRIPTION

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